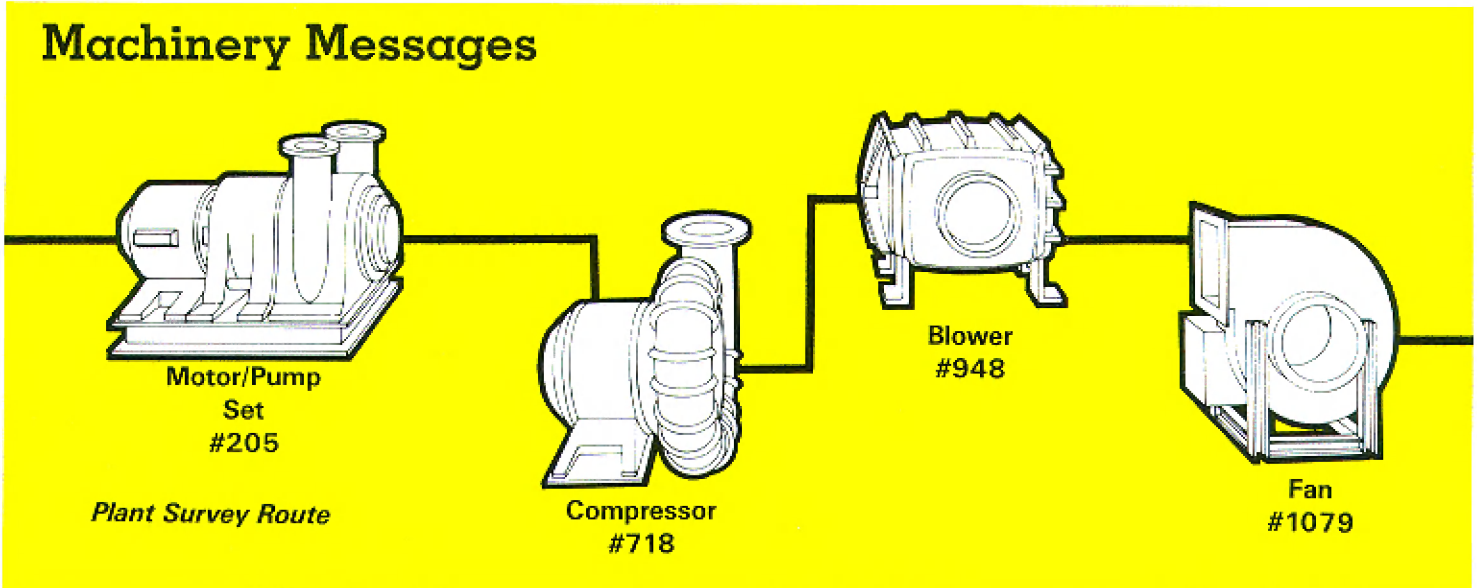

Predictive Maintenance through the monitoring and diagnostics of rolling element bearings

The predictive maintenance philosophy of using vibration information to lower operating costs and increase machinery availability is gaining acceptance throughout industry. Since most of the machinery in a predictive maintenance program contains rolling element bearings, it is imperative to understand how to monitor and diagnose problems associated with them. Bently Nevada has adopted a two-part philosophy with regard to rolling element bearing monitoring and diagnostics: (1) the monitor system will provide adequate warning to avert catastrophic machine failures and (2) diagnostic data will be available so that when warning is given, the bearings will have visible damage. This philosophy should be kept in mind during the following discussion.

Rolling element bearing characteristics

Any discussion of monitoring and diagnostics for rolling element bearings would not be complete without a comparison of the techniques used for fluid film bearings. The construction of a fluid film bearing is such that the shaft is supported by a fluid film during operation. By design, the shaft can experience motion relative to the bearing. Because of this freedom of motion, the industry-accepted vibration measurement for a fluid film bearing machine is a shaft relative measurement, i.e., proximity probe.

A rolling element bearing, by design, has extremely small clearances which do not allow a significant amount of shaft motion relative to the bearing (Figure 1). Forces from the shaft are transferred through the rolling elements to the bearing outer ring and then ultimately to the bearing housing. Because of this transmission, a casing (bearing housing) measurement is normally acceptable for monitoring machines with rolling element bearings. However, as explained later in this discussion, a method called REBAM® is available from Bently Nevada Corporation that allows vibration measurements directly at the bearing outer ring. This direct measurement greatly enhances bearing vibration data, and in some cases, this is the only measurement that can provide adequate vibration information.

Shaft relative vibration measurements (i.e., proximity probe) are also useful when clearances increase during failure and for observation of rotor problems that are not related to bearings. A classic characteristic of rolling element bearings is the generation of specific vibration frequencies based on the bearing geometry, number of rolling elements and the speed at which the bearing is rotating. These "bearing-related" frequencies, typically in the range of 1 to 7 times the element passage rate (EPx), are generated even by a new bearing, but the amplitudes are very small. Element passage rate is defined as the rate at which the rolling elements pass a point on either the inner or outer bearing ring. As a bearing fails, these bearing-related frequencies (Prime Spike) will increase in amplitude.

Observation of these bearing-related signals is used to diagnose rolling element bearing-related vibration problems and to determine what has failed in the bearing. This precise diagnosis may aid the analyst's credibility, but from a plant manager's viewpoint, it is not as necessary to identify *what* in the bearing is failing, as it is *essential* to determine *when* the bearing must be replaced to avert a machine failure. The methodology for using the bearing-related frequencies to achieve the plant manager's goal is outlined later in this discussion.

Vibration characteristics of rolling element bearings

The vibrations produced by machines with rolling element bearings occur in three frequency regions.

1. Rotor vibration region

Rotor-related vibrations normally occur in the range of 1/4 to 3 times shaft rotative speed (1/4X – 3X) and are best measured in terms of velocity or displacement. Many rolling element bearing failures are the direct result of a rotor-related malfunction (e.g., unbalance, misalignment, or rotor instability). Rotor-related malfunctions must be corrected to eliminate bearing overloading and subsequent failure. Most general purpose equipment with speeds from 1200 to 3600 rpm generate rotor-related vibration signals between 10 and 500 Hz (600 to 30 kcpm). It is, therefore, imperative for diagnostics to monitor this frequency range in order to determine when/if a bearing failure is caused by a rotor related malfunction. Without this data, the rotor-related malfunction would remain undetected and bearings will continue to fail and need periodic replacement.

2. Prime Spike region

The second vibration frequency region to monitor for machines with rolling element bearings is the Prime Spike (element passage) region. As previously mentioned, a rolling element bearing generates characteristic frequencies based on its geometry and speed. Prime Spike is a term used by Bently Nevada to describe a vibration frequency range which includes those bearing frequencies that are generated by the rolling elements traversing either an inner or outer race flaw. This frequency range is normally 1 to 7 times the element passage rate (1-7 EPx). Vibrations in this range can be measured effectively in terms of acceleration, velocity or displacement. Field studies indicate that approximately 90% of all bearing failures are related to either an inner or outer race flaw. The other 10% are related to either a rolling element flaw or a cage flaw, both of which generate frequencies that appear in the rotor vibration region. By establishing a frequency band around the predominant bearing failure frequencies and filtering out the rotor-related vibration frequencies, it is possible to gain improved monitoring information of bearing condition. A computer analysis of 428 different bearings shows that the Prime Spike region (1-7 EPx) covers the bearing frequencies of many rolling element bearings.

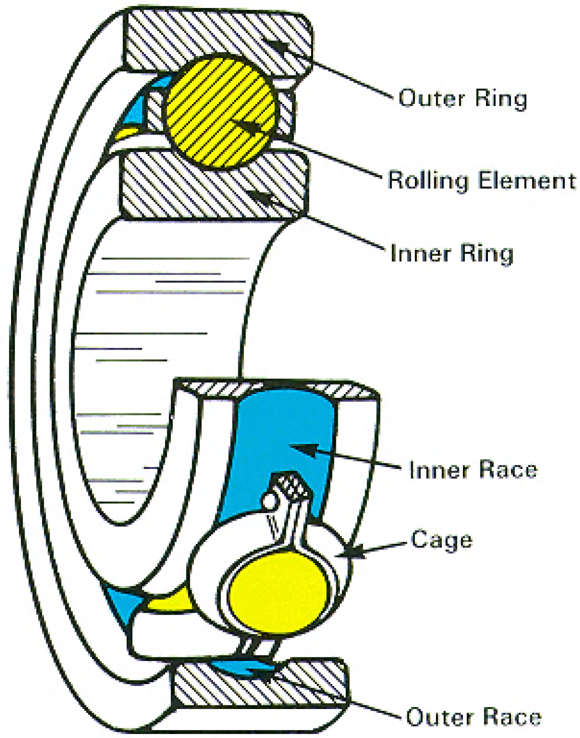

Figure 1
Components of a rolling element bearing

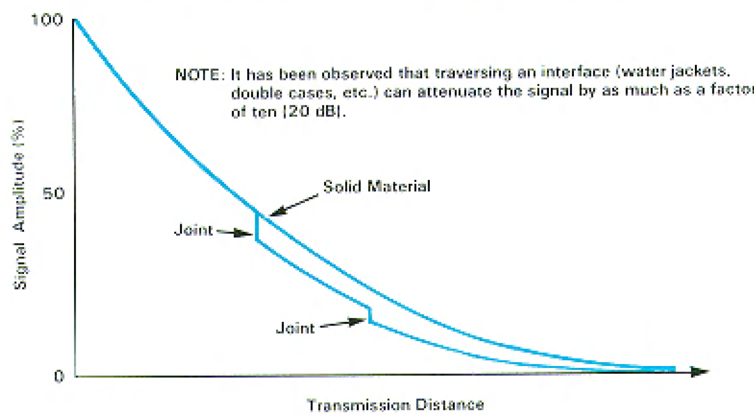

Figure 3
Signal decay vs transmission distance

3. High frequency (Spike Energy) region

The third region is the high frequency (Spike Energy) region. This region covers frequencies from 5 kHz to approximately 25 kHz and is measured in terms of acceleration. If high frequency region measurements are used for bearing failure detection, they should be used as a supplement to measurements made in the

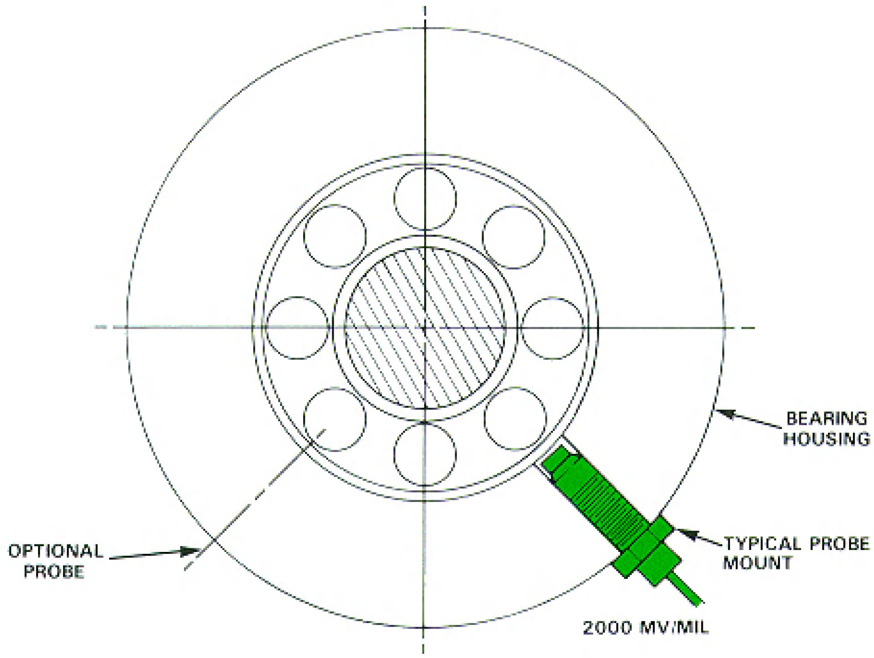

Figure 2
Typical REBAM probe mount

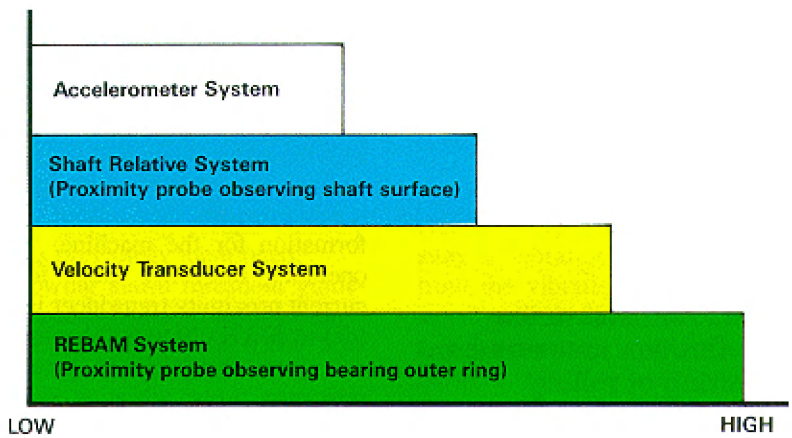

Figure 4
Transducer system comparative signal-to-noise ratios

rotor-related and Prime Spike regions. High frequency measurements have two primary uses:

1. High frequency signals occasionally provide an early indication of a bearing problem at the prefailure stage. Care must be exercised because "self-peening" of bearing flaws results in decreasing readings in this frequency region as a bearing failure progresses.
2. High frequency signals are useful to help detect certain other machine malfunctions such as cavitation, rubs, steam or gas leaks, valve problems, blade passage or gear mesh problems. High frequency vibration energy attenuates very rapidly with distance from the source. This can be both bad and good. Bad, in that one needs to be very close to the source to obtain data; good, in that the localized nature of the vibration can be used to isolate the source of a problem.

Based on observation of many rolling element bearings in the field by Bently Nevada Corporation, and many of our customers, most of the information on the performance of rolling element bearings and warning of their failure occurs in the Prime Spike region (1-7 EPx). Information about *rotor behavior* generally occurs in the region between 1/4 and 3 times rotative speed. Information at very high frequencies (8 EPx and higher to the mega hertz region) *may* contain very early warning information, as well as other data concerning machinery condition (e.g., rubs, gear noise, cavitation, valve noise, etc.). However, the *principal* and *vital* data for rolling element bearings is contained in the Prime Spike region (1-7 EPx).

Causes of failure in rolling element bearings

A rolling element bearing has a finite life and *will* fail due to fatigue, even if operated under ideal design conditions.

Rolling element bearing manufacturers realize this fact and have developed design life limits (L_{10}/B_{10}) to let users know how long a bearing should last when installed and operated within design limits. L_{10}/B_{10} is defined as the rating life of a group of apparently identical rolling element bearings operating under identical loads and speeds with a 90% reliability before the first evidence of fatigue develops. Unfortunately, most "real world" installations are not under ideal conditions and the bearings prematurely fail well before reaching their design life. Most premature bearing failures can be attributed to one or more of the following causes:

1. Excessive loading
   a. Steady-state (e.g., misalignment or static load)
   b. Dynamic (e.g., unbalance or rotor system instability)
2. Improper lubrication (insufficient or excessive)
3. External contamination
4. Improper installation
5. Incorrect sizing (e.g., wrong design)
6. Exposure to vibration while not rotating (false brinelling)
7. Passage of electric current through the bearing

When analyzing premature rolling element bearing failures, it is important to not only determine that the bearing is failing, but also to determine the underlying cause of that failure. The above list shows the major causes of premature bearing failure and can be used as an initial

guide to determine the reason for a bearing failure. To ensure success, elimination of premature bearing failures must be a major goal of any predictive maintenance program.

A rolling element bearing progresses through three failure stages:

1. Prefailure
2. Failure
3. Near catastrophic/catastrophic

NOTE: Each of these different failure stages exhibit specific vibration characteristics which require specific diagnostic/monitoring techniques.

Prefailure stage—During the prefailure stage, the bearing is in the earliest stages of failure. It develops hairline cracks or microscopic spalls that are not normally visible to the human eye. During this stage there may be an increase in the high frequency (> 7 EPx) vibration produced by the bearing. If temperature or Prime Spike vibration measurements are taken during this stage, the levels will be normal. At this stage, the bearing usually has a significant amount of safe operating life left and it is not economical to replace it at this time.

Failure stage—During the failure stage, the bearing develops flaws that are visible to the human eye. At this stage, the bearing usually produces audible sound and the temperature of the bearing will rise. Vibration amplitudes in the "bearing related" range (Prime Spike) reach easily detectable levels. Once the failure stage is reached, it is necessary to either change the bearing or increase the frequency of monitoring to estimate how long the bearing will safely operate before causing a catastrophic machine failure. This stage is considered the economical time at which to replace the bearing.

If the bearing is not removed during the failure stage, it will eventually enter the final progression of failure, the near catastrophic/catastrophic stage.

Near catastrophic/catastrophic stage—When the bearing enters this stage, rapid failure of the bearing is *imminent*. Audible noise produced by the bearing significantly increases and the bearing temperature increases until the bearing overheats. Rapid wear causes the bearing clearance to increase, which then allows significant shaft motion relative to the bearing. Since a rolling element bearing is designed to *restrict* shaft motion, it can be very dangerous to allow the bearing to reach this stage due to the probability of creating a rub within the machine. Bearing-related (Prime Spike) vibration amplitude levels will show significant increases in this stage. High frequency vibration data may be unreliable in this stage and caution should be used in its interpretation. Due to "self-peening" of the bearing flaws, high frequency amplitude levels often *decrease* during this stage and it can *appear* that the bearing is in an earlier stage of failure. The occurrence of this "self-peening" phenomena is especially true for low speed machines.

"... it is not as necessary to identify what in the bearing is failing, as it is essential to determine when the bearing must be replaced to avert a machine failure."

Transducers and instrumentation for vibration measurement and monitoring of rolling element bearings

1. REBAM instrumentation system

REBAM is an acronym for **R**olling **E**lement **B**earing **A**ctivity **M**onitor. The REBAM system uses a high-gain, low-noise eddy current proximity transducer that is installed in the bearing housing observing the bearing outer ring (Figure 2). The REBAM transducer measures the very small (microinch/micrometre) deflection of the outer ring as the rolling elements pass the area observed by the transducer. These deflections are measured in terms of displacement. The operating frequency range for the REBAM transducer system is from 0 Hz (dc) to 10 kHz (0 to 600 kcpm). The REBAM system is a direct and very sensitive method of rolling element bearing measurement. It offers a very high signal to-noise ratio, as compared to casing-mounted acceleration or velocity measurements.

Through the use of electronic filters, the REBAM vibration signal is separated into rotor vibration and Prime Spike regions as previously discussed. The REBAM Prime Spike values occur in the range of 20 to 50 microinches (0.5 to 1 micrometres) peak-to-peak when the bearing is in good condition and increases to 100 to 300 microinches (3 to 8 micrometres) peak-to-peak when deterioration of the contacting surfaces occurs. A common practice is to take reference data to determine its "normal" level when the bearing is in a known good condition. Alert and danger alarm levels are then typically set at three and ten times the "normal" level for the bearing. Field tests confirm that by using these alarm levels, adequate failure protection is usually provided.

2. Shaft relative instrumentation system

Shaft relative measurements (i.e., eddy current proximity transducer) have been accepted industry-wide as the primary measurement for vibration monitoring and diagnostics of fluid-film bearing machines. However, a proximity probe based system can be used effectively to monitor rolling element bearing performance and it also provides rotor-related vibration information for the machine. The typical operating frequency range for an eddy current proximity transducer is from 0 Hz (dc) to 10 kHz (0 to 600 kcpm). As is the case with the REBAM transducer, the proximity probe vibration signal can be separated with electronic filters into the rotor vibration and Prime Spike regions. As previously discussed, this signal separation provides the information necessary to effectively analyze and monitor rolling element bearing machinery.

3. Casing vibration instrument systems

Rolling element bearing condition can be monitored by using casing measurements. Overall velocity or displacement, Prime Spike velocity, and the high frequency acceleration region can be used. Bently Nevada can provide accelerometer or velocity transducer-based systems to monitor rolling element bearing condition. Overall casing velocity or displace ment provides a means for determining the general mechanical condition of rolling element bearing machinery.

For a velocity transducer based system, the frequency range used is from 10 Hz to 1 kHz (600 cpm to 60 kcpm). For an accelerometer based system, the frequency range used is from 10 Hz to 2.5 kHz (600 cpm to 150 kcpm). This frequency range includes the rotor vibration frequency region and overlaps the lower end of the Prime Spike frequency region. This range gives very good indication of rotor-related malfunctions and it is also somewhat sensitive to bearing-related problems.

As stated previously, the Prime Spike region is used by Bently Nevada to monitor the rolling element bearing-related frequencies (inner/outer race defects). By filtering out the rotor-related vibration signals (i.e., 1X, 2X, etc.), it is possible to get better signals related to the rolling element bearing condition. The Prime Spike frequency region includes the fundamental element passage frequency (EPx) and harmonics up to 7 EPx.

If an accelerometer-based system is used, Prime Spike and high frequency measurements are available. However, due to the noise susceptibility problems previously mentioned, the high frequency measurements should be used only as a possible early indicator of impending rolling element bearing problems. The high frequency range used by Bently Nevada is from 5 kHz to 25 kHz (300 kcpm to 1500 kcpm). High frequency measurements are useful when diagnosing certain machine malfunctions previously mentioned.

The following alarm threshold guidelines were established for the three diagnostic techniques based on field tests conducted by Bently Nevada:

1. Overall velocity: 0.3 in./sec. (7.7 mm/s) pk.
2. Prime Spike region: 0.1 to 0.15 in./sec. (2.5 to 3.8 mm/s) pk.
3. High frequency region: 3 to 4 g pk.

NOTE 1: These high frequency levels, as measured with the Bently Nevada Trendmaster accelerometer, are typically 10 times higher in amplitude in this region than competing units.

NOTE 2: These alarm threshold levels for balance-of-plant equipment should be considered as an *initial guide only* . The levels may need adjusting up or down, depending on how an individual monitored machine behaves.

When using casing measurement systems, two key factors should be considered: (1) signal amplitude versus transmission distance and (2) the measurement's susceptibility to noise. The farther away a vibration measurement is made from the vibration source, the more the signal will be attenuated. Most rolling element bearing machines have joints between machine parts which further attenuates the signals. Figure 3 shows that there is a sharp vibration signal attenuation at each joint. The closer the measurement is made to the machine vibration source, the better the measurement. For a rolling element bearing, it is suggested to be within 1 to 2 inches (25 to 50 mm) from the bearing. Another fact that must be considered is a comparison of the various transducer systems' signal-to-noise ratios. System signal-to-noise ratio is defined as the ratio of the amplitude of a desired signal at any point to the amplitude of noise signals at that same point. A comparison of the signal-to-noise ratios for the various transducer systems is shown in Figure 4. If not carefully considered, these two factors can have a large negative impact on the success of using casing measurements for monitoring.

The Trendmaster is designed as a predictive maintenance tool specifically for machines with rolling element bearings. The instrument derives and stores three types of amplitude data from each transducer measurement: Overall Velocity, Prime Spike Velocity, and High Frequency Acceleration.

Summary

Based on the Bently Nevada two-part philosophy of (1) providing adequate warning to avert machine failures and (2) removing bearings only when they are likely to have visible evidence of an impending failure, the following conclusions are drawn:

1. Rotor vibration and Prime Spike displacement (obtained from permanently-installed REBAM probes) or overall velocity and Prime Spike velocity (obtained from a casing-based measurement), are the primary techniques used to monitor rolling element bearings. These measurements should be used to determine when to remove the bearing.

2. High frequency measurements are to be used only as a *possible indicator* of impending rolling element bearing failure and should generally not be used as the primary indicator in determining when to replace the bearing.

For a copy of this article and additional information on rolling element bearings, check the appropriate box on the reader service card. ■